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The Potential Impact of Rising Salinity on the Salton Sea Ecosystem

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Introduction

The Salton Sea is a body of water with no outlet. Water which flows into the Sea can evaporate away but dissolved (and suspended) material remain behind. Based on its volume at a surface elevation of -227 feet and an annual salt inflow of 4 million tons, the Sea's salinity is estimated to be rising approximately 0.4 ppt per year from its current value of about 43-44 ppt.

This inevitably increasing salinity will exert its effect on the Sea's ecosystem by first affecting the physiology of organisms. The effect on physiology can be direct, by affecting the performance of specific metabolic processes, or indirect, by causing a redirection of energy toward osmoregulation and away from growth, reproduction and other functions. In either case, increasing salinity eventually causes sufficient physiological stress on the individuals of a species that their population numbers fall due to:

1) greater susceptibility to other physical factors such as low oxygen and extreme temperatures;
2) greater vulnerability to biological factors such as disease and predators; and/or
3) impaired reproduction.

Any one of these effects can be sufficient to cause the loss of a species from the Salton Sea ecosystem. If however, none of these are sufficient, loss of the species is merely postponed until the rising salinity exceeds an absolute tolerance level and direct mortality of at least one life stage occurs.

Whatever the exact mechanism behind the loss of individual species, the net result of increasing salinity will undoubtedly be a gradual reduction in the diversity of the Salton Sea's biota. The goal of this issue paper is to review and analyze the currently available relevant information on the Salton Sea ecosystem and its constituent species and then estimate the approximate salinity values at which key changes in species composition will occur.

The approach taken below is basically autoecological, i.e. the available information on salinity tolerance is reviewed separately for each species inhabiting the Sea. Although this approach neglects the potential for synergistic ecological effects between physiological and biological factors in determining the overall ecosystem impacts, there is little alternative due to the widely varying amounts of information available for different species.

Invertebrates

Rotifers

The dominant rotifer species in the Salton Sea is *Brachionus plicatilis,* a species common in estuaries throughout the world. There is a large scientific literature on this species because of its value as food for fish larvae but most work on salinity tolerance concerns the freshwater end of the salinity spectrum. Timms (1993) collected this species from lakes with salinities up to 76 ppt in Australia.

Epp and Winston (1977) reported that *B. plicatilis* is essentially an osmoconformer and that rotifers collected from an inland (Colorado) saline pond required acclimation to tolerate salinities of artificial ocean water over 35 ppt. Minkoff et al. (1983) reported reduced (compared to lower salinities) but successful hatching of resting eggs in 40 ppt ocean water.

Mustahal et al. (1991) examined the ability of five strains of *B. plicatilis* to adapt to salinities up to 45 ppt by adding rock salt (NaCl) to ocean water. All five strains continued to show improvement in reproduction after 75 days of culture at 45 ppt, although reproduction was generally higher at lower salinities.

Lubzens et al. (1985) supplemented ocean water with artificial ocean salt to create hypersaline conditions and found that *B. plicatilis* was able to slowly reproduce parthenogenetically at 48 ppt. Sexual reproduction (resting egg production) virtually disappeared by 35 ppt in their studies.

Pascual and Yufera (1983, cited in Miracle and Serra 1989) successful reproduction at 50 ppt and Lubzens et al. (1985) at 48 ppt. Pozuelo and Lubian (1983) concentrated ocean water by evaporation and found reduced population growth at 40 ppt (compared to 10 ppt) and no growth at 50 ppt.

Copepods

The cyclopoid copepod *Apocyclops dengizicus* is a major component of the Salton Sea zooplankton. Timms (1987) collected this species from Australian sites with salinities up to 75 ppt.

Dexter (1993) was able to induce reproduction in *A. dengizicus* in culture at salinities up to 68 ppt although the cultures maintained their density only up to 51 ppt. Adults were able to survive for 120 days at 79 ppt and 60 days at 107 ppt.

Dexter (1995) reported the occurrence of the benthic harpacticoid copepod *Cletocamptus deitersi* in the Salton Sea. She was able to successfully culture this species for 120 days at salinities up to 80 ppt produced by the evaporation of Salton Sea water. At 85 ppt the survivorship of nauplii larvae faltered. Adults were able to survive and copulate at 107 ppt.

Pileworm

The pileworm, *Neanthes succinea,* is probably the most important member of the Salton Sea benthos. Hanson (1972) reported 96-hour survivorship of 93.3% for pileworms in Salton Sea water concentrated to 67.5 ppt.

Kuhl and Oglesby (1979) also utilized concentrated Salton Sea water to study the influence of hypersalinity on pileworm survivorship and reproduction. Survivorship at 65 ppt was approximately 50% of control survivorship, with substantial reduction from that at 70 ppt and virtually no survival at 85 ppt. Pileworm maturation into the heteronereid breeding form was reduced 50% from controls at 55 ppt. No heteronereid production was observed over 65 ppt. Egg fertilization was substantially reduced at 50 ppt and was completely unsuccessful over 55 ppt. Larval development was never observed at salinities over 50 ppt.

Barnacle

The Salton Sea barnacle population of *Balanus amphitrite saltonensis* (Rogers 1949), originated around 1943 with barnacles transported via Navy buoys or flying boats from San Diego Bay (Hilton 1945). Flowerdew (1985) compared the genetic composition of six populations of *B. amphitrite* and recommended eliminating *B. a. saltonensis* as a subspecies, but Raimondi (1992) detected differences in larval morphology and development which remained consistent during culturing, and which therefore, are probably attributable to genetic differentiation.

Crisp and Costlow (1963) studied the influence of salinity on embryonic development of North Carolina *B. amphitrite* utilizing concentrated ocean water. Larval development time was extended by 50% at 60 ppt and 92% at 70 ppt; there was no development at 80 ppt. Larval survival fell to 50% of controls at 55 ppt.

Perez (1994) studied hypersalinity effects on Salton Sea barnacles by adding artificial ocean salts to actual ocean water (not Salton Sea water). Survivorship over four weeks was not significantly affected at salinities up to 70 ppt but mortality was complete within two weeks at 80 ppt. Feeding rate was unchanged at salinities up to 60 ppt but was 20% or less of control rates at 70 or 80 ppt. Reproduction appeared unimpaired at 50 ppt.

Simpson (1994) found that a variety of structural traits, such as carapace wall thickness and attachment strength, as well as growth rate, all declined at salinities over 48 ppt.

Amphipod

The amphipod crustacean *Gammarus mucronatus* can be abundant in the shallow portions of the Sea. This species has been collected from Texas bays with salinities as high as 50 ppt (Hedgpeth 1967) and has reportedly been maintained in culture at 79 ppt (Debbie Dexter personal communication cited in Hart 1994).

Corixid

The waterboatman *Trichocorixa reticulata* can also be locally abundant within the Salton Sea. Jang and Tullis (1980) studied the osmoregulatory ability of this species by augmenting hypersaline water (50 ppt) from San Francisco Bay salt ponds with artificial ocean salts, and found that *T. reticulata* has an excellent capability to regulate its body water content up to a salinity of 100 ppt. Euliss et al. (1991) report the collection of this species from California Central Valley evaporation ponds with conductivities "extending to 6 times seawater."

Fish

Longjaw Mudsucker

The longjaw mudsucker (*Gillichthys mirabilis*) is a mudflat-inhabiting member of the goby family. It has reputedly been collected from sites in the northern Gulf of California at salinities as high as 82.5 ppt (Lars Carpelan, personal communication cited in Barlow 1963). Lonzarich and Smith (1997) imply that this species may reproduce at salinities up to 75 ppt.

Sailfin Molly

The sailfin molly (*Poecilia latipinna*) is common in the shoreline pools and drains along the periphery of the Salton Sea. Herre (1929) reported that this species was "very abundant" in Philippine salt work ponds at 87 ppt but absent from ponds at 94 ppt. By acclimating mollies very gradually to ocean water supplemented with artificial ocean water salts, Nordlie et al. (1992) obtained 95.7% survivorship (over two weeks) at 80 ppt and 43.1% at 85 ppt.

Desert Pupfish

The desert pupfish, *Cyprinodon macularius*, is the only currently resident fish species endemic to the Salton basin. It was listed as a federally endangered species in 1986 (USFWS 1986).

Desert pupfish have been collected from Salton Sea shoreline pools with salinities as high as 90 ppt (Barlow 1958). Growth is faster at 35 and 15 ppt than in 55 ppt ocean water concentrated by evaporation (Kinne 1960).

Kinne and Kinne (1962) created hypersaline water with artificial ocean salts and found that desert pupfish eggs successfully developed in salinities of 70 ppt at temperatures below 33°C, although with longer development times and higher mortality than at lower salinities. At 33°C development time rose precipitously, suggesting severe stress. Development was not successful at 85 ppt.

Sargo

Sargo (*Anisotremus davidsonii*) eggs and larvae are planktonic. Lasker et al. (1972) presented the results of experiments utilizing Salton Sea water concentrated by evaporation on larval mortality through 96 hours. The first series of experiments, performed in 1968, showed a clear increase in larval mortality at 40 ppt and higher, compared to the control (35 ppt). Lasker et al. also claimed that two 1970 experiment series "similarly showed a clear detrimental effect of salinity on survival rate at 40 ppt and higher." However, the 1970 experiments suffered from extremely high mortality in the controls and, in fact, one series shows higher 96 hour survivorship at 55 ppt (50.5%) than at 35 ppt (12.9%). Lasker et al. also reported a high incidence of larval abnormalities, particularly bent tails in all treatments.

Hanson (1970) also concentrated Salton Sea water by evaporation and exposed juvenile sargo for 96 hours to high salinities without acclimation. Survivorship of juvenile sargo appeared to decline markedly at salinities between 42.5-47.5 ppt, reaching zero at 62.5 ppt, but the data were not monotonic.

Matsui, Lattin et al. (1991a) concentrated Salton Sea water by reverse osmosis and were able to acclimate adult sargo to 55 ppt over a five month period. Adult sargo held in tanks at 35 through 45 ppt spawned naturally but no spawning occurred in tanks at 50 or 55 ppt. In 96 hour experiments egg mortality showed no clear increase from 35 to 55 ppt whereas larval mortality increased steadily over the same range, reaching 100% at 55 ppt.

Brocksen and Cole (1972) studied the metabolic maintenance requirements in juvenile sargo in Salton Sea water concentrated by evaporation. They found maintenance requirements lowest at 33 ppt and highest at 45 ppt (the highest salinity they tested). They characterized these results as indicating a "rather severe stress" at 45 ppt.

Bairdiella

Like sargo, gulf croaker (*Bairdiella icistia*) eggs and larvae are planktonic. There are repeated reports that the Salton Sea croakers have a high level of developmental deformities (e.g. Whitney 1961, Matsui et al. 1992). These deformities may be due to an apparent genetic founder effect which is discernible in the form of a low occurrence of rare alleles, although the overall rate of genetic heterozygosity is comparable to other fish populations (Beckwitt 1987). If the deformities are, in fact, a result of a genetic founder effect, then the ability of the Salton Sea croaker population to adapt to rising salinity may be genetically limited.

Hanson (1970) reported that juvenile bairdiella transferred directly to higher salinities created by evaporating Salton Sea water tolerated 52.5 ppt for 96 hours, although there was 60% mortality at 55 ppt. Mortality of yearling bairdiella began at 52.5 ppt (40%) and increased to 60% at 55 ppt and 93.3% at 62.5 ppt, until no fish survived at 75 ppt.

Lasker et al. (1972) detected a marked increased in egg and larval mortality at salinities over 45 ppt although control mortality was also high. They also reported a high incidence of larval abnormalities, particularly bent tails.

May (1975a, 1975b) performed detailed experiments on the effect of salinity and temperature on various aspects of bairdiella reproduction utilizing artificial ocean water. The activity period of croaker spermatozoa fell from 3 minutes at 35 ppt salinity to 1.5 minutes at 45 ppt. Fertilization success and hatching rate declined markedly at salinities over 45 ppt and 40 ppt, respectively. There was also a significant inverse interaction between temperature and salinity: development at high salinities over 45 ppt was most successful at temperatures below 30°C and vice versa. Larvae reared at salinities over 40 ppt and/or temperatures over 30°C had a notable frequency of spinal deformities.

May (1976) compared croaker development in ocean water versus Salton Sea water. At 35 ppt fertilization success was higher in Salton Sea water (72.9%) than ocean water (53.6%). Utilizing artificial ocean water and artificial Salton Sea water (deionized water with salts added to mimic the ionic composition of natural Salton Sea water) May also found that this fertilization advantage extended up to 45 ppt. For larval survivorship however, the situation was reversed. No larvae survived longer than two days in artificial Salton Sea water of 35 and 45 ppt and only a small percentage in natural Salton Sea water whereas many larvae survived over four days in both natural and artificial ocean water. May concluded that this disparity in larval survivorship was due to the "unusual combination of ions [in Salton Sea water]."

After reaching this conclusion, May (1976) then asked the question "how can [bairdiella] be so successful in the Salton Sea if only 5 or 6% of the larvae survive to the feeding stage?" His answer was to point out 1) the high fecundity of fish with pelagic eggs and larvae; 2) the paucity of invertebrate predators so common in the oceans; and 3) the high productivity of the Salton Sea, i.e. the abundance of zooplankton larval fish food.

Brocksen and Cole (1972) found that bairdiella metabolic maintenance requirements in evapoconcentrated Salton Sea water were lowest at 37 ppt, rose over 136% at 41 ppt, and went even higher at 45 ppt.

Tilapia

The Salton Sea tilapia population is basically a strain of *Oreochromis mossambicus* (Costa-Pierce and Doyle 1997). The salinity tolerance of tilapia species has been reviewed by Stickney (1986).

Although they did not give much detail, Whitfield and Blaber (1979) stated that *O. mossambicus* had been collected from South African coastal lakes with salinities up to 120 ppt. Potts et al. (1967) studied sodium and water balance in *O. mossambicus* and established that five to ten week old fish can tolerate 70 ppt (ocean water supplemented with NaCl) indefinitely. Popper and Lichatowich (1975) reported that *T. mossambica* reproduction was so prolific in Fiji aquaculture ponds at salinities up to 49 ppt that it was necessary to introduce predators for population control.

Kultz and Jurss (1993) studied ion transport in gills of adult *O. mossambicus* acclimated and then maintained for at least five weeks in 60 ppt water created with a combination of artificial ocean salt and NaCl. Kultz and Onken (1993) did the same for juvenile *O. mossambicus*. Assem and Hanke (1979) succeeded in acclimating juvenile *O. mossambicus* to artificial ocean water of 60 ppt.

There is a small amount of information on the interaction between salinity and organic chemicals. Dange (1986) found that 40-50 gram *O. mossambicus* were more susceptible to disruption of gill osmoregulatory mechanisms by toluene and naphthalene at 35 ppt than at 20 ppt. It could be inferred that even higher salinities would make this species even more vulnerable to organic pollutants.

Orangemouth Corvina

Although corvina is the most sought after game fish in the Salton Sea, its large size makes it a more difficult experimental organism than the other Salton Sea fish species and it has therefore, received the least amount of study. Hanson (1970) reported that 100% of juvenile corvina survived 96 hours in evapoconcentrated Salton Sea water without acclimation at 52.5 ppt and over 90% survived at 55 and 57.5 ppt, but that mortality was complete at 62.5 ppt.

Brocksen and Cole (1972) found that corvina assimilation efficiency in evapoconcentrated Salton Sea water was higher at 37 ppt (72%) than at 45 ppt (59%). Oxygen consumption in juvenile corvina (up to 30 grams) was markedly higher at 45 ppt than at 41 ppt, particularly for larger fish.

Matsui, Lattin et al. (1991b) found that corvina were able to were able to grow in Salton Sea water concentrated by reverse osmosis at salinities up to 55 ppt. Although oocyte maturation also occurred at salinities up to 55 ppt, spawning could only be induced (with the aid of hormone injections) at 35 and 40 ppt; spawning did not occur at 45 and 50 ppt under their experimental conditions. Egg mortality was generally below 10% at salinities up to 55 ppt but larval mortality was about 17% at 40 ppt and reached 50% at 45 ppt.

Discussion

There is a varying but not inconsiderable body of information available on the salinity tolerance of species inhabiting the Salton Sea. This information can be divided into four categories:

- Collection. This refers simply to the salinity at a site where an organism was collected in nature. Since there is always a chance that an individual was collected while transiting an area of higher salinity that it normally inhabits, this salinity value could be higher than values in any of the other categories.
- Life Stage Survival. This category is defined as the maximum salinity, in experimental work, at which one or more life stages of a species can survive for an extended time, but where completion of the entire life cycle has not been established.
- Life Cycle Completion. This category is defined as the maximum salinity, in experimental work, at which completion of a species' entire life cycle has been demonstrated. This salinity should theoretically always be lower than the life stage survival salinity.
- Population Maintenance. This category is defined as the maximum salinity, in experimental work, at which population growth has been demonstrated and should theoretically be lower than the life cycle and life stage salinity values. Note also that, because this value is still based on experimental (laboratory) work, it does not take biotic interactions (competition, predation, parasitism, disease, etc.) into account.

Table 1 is an attempt to organize the literature reviewed above into these four categories of salinity tolerance information. Population maintenance salinity values for the fish species are generally lacking because of the greater logisitical requirements for maintaining large game species. For several fish species the ability to complete the life cycle was assumed when egg and juvenile stages were demonstrated to be tolerant of a given salinity.

Table 1. Summary of salinity occurrence and tolerance data for species inhabiting the Salton Sea.

Species	Collection	Life Stage Survival	Life Cycle Completion	Population Maintenance
Brachionus plicatilis (rotifer)	76	50	48-50	40
Apocyclops dengizicus (copepod)	75	79	68	51
Cletocamptus deitersi (copepod)	--	107	80	80
Balanus amphitrite (barnacle)	--	60	60	50
Nereis succinea (pileworm)	--	67.5	50	--
Gammarus mucronatus (amphipod)	50	79	--	--
Trichocorixa reticulata (water boatman)	200	100	--	--
Cynoscion xanthulus (orangemouth corvina)	--	57.5	40	--
Bairdiella icistia (Gulf croaker)	--	55	55	--
Anisotremus davidsonii (sargo)	--	52.5	50	--
Oreochromis mossambica (tilapia)	120	70	50	--
Cyprinodon macularius (desert pupfish)	90	70	70	--
Poecilia latipinna (sailfin molly)	87	80	--	--
Gillichthys mirabilis (longjaw mudsucker)	82.5	--	75	--

In general, as expected, salinity tolerance values for each species decline across the table. For *Brachionus plicatilis* however, the population maintenance salinity value is lower than the Sea's current salinity. For this species at least, the scientific literature clearly does not reflect the situation in the Salton Sea.

So, what kind of predictions regarding the impact of rising salinity on the Salton Sea ecosystem can be made from this information? Answer: highly provisional ones. Among the caveats which must be attached to any projections are:

- the lack of complete life cycle salinity tolerance data for several species and population maintenance data for most;
- even for those species with comparable data, the varying use of Salton Sea water, ocean water, and commercial sea salts for the preparation of experimental media;
- potential interactions between pollutants and salinity tolerance (Bonga and Lock 1992); and
- the difficulty in predicting synergisms between biotic interactions and salinity stress (Hart 1994, Simpson 1994).

Nevertheless, with these caveats in mind, a basic sequence of impacts can be suggested by taking the data from Table 1 at face value:

1. <u>Loss of sportfishery</u>. The demise of corvina, croaker and sargo has of course, been predicted for some years but they continue to reproduce. The available evidence however, still indicates that corvina reproduction might fail at any time and certainly by 50 ppt together with croaker and sargo, leaving tilapia as the only species large enough for sport fishing.
2. <u>Loss of tilapia</u>. By 60 ppt the salinity tolerance of tilapia has probably been exceeded. This leaves desert pupfish, sailfin mollies, and longjaw mudsuckers as the only fish species inhabiting the Sea. These species will probably be able to expand their populations when tilapia declines but their small sizes make them unlikely candidates to replace tilapia in the diets of fish-eating birds.
3. <u>Loss of microzooplankton</u>. At about 70 ppt the cyclopoid copepod disappears (the rotifers died off some time ago) leaving no true zooplankton. This could have significant effects on the species composition of the phytoplankton with possible implications for nutrient cycling and the overall productivity of the Sea.
4. <u>Loss of all fish</u>. At about 80 ppt even desert pupfish and sailfin mollies reach their salinity tolerance limits. At this point the Salton Sea ecosystem begins to bear a significant resemblance to that of Mono Lake, dominated by specialized halotolerant invertebrates such as brine shrimp and brine flies.

Conclusions

Using the available information, it is possible to sketch a general description of probable changes in the Salton Sea's ecosystem due to rising salinity. It is very difficult however to confidently assign salinity values at which specific changes will occur.

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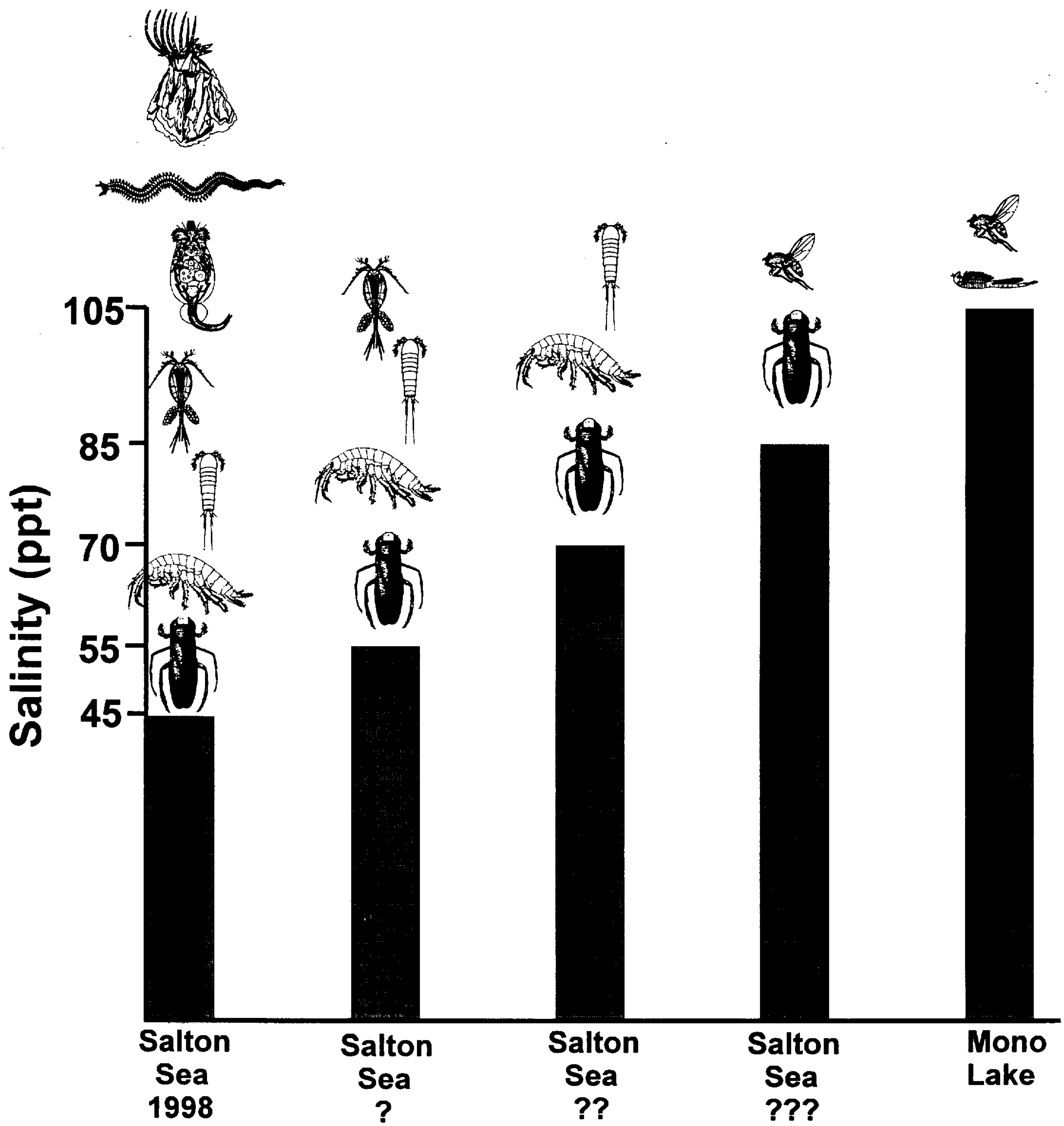
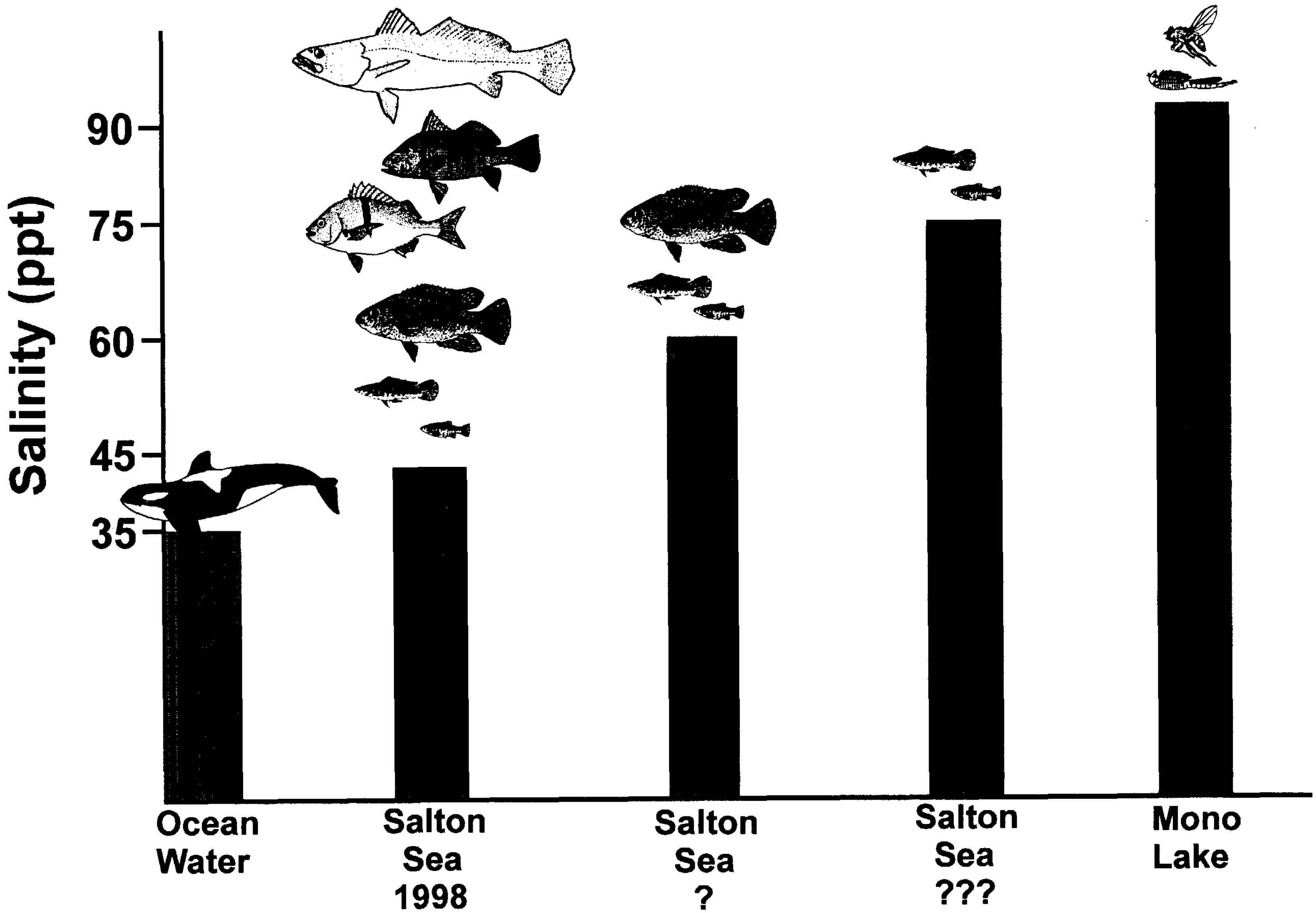
Probable Influence of Elevated Salinity on the Invertebrate Fauna of the Salton Sea



Probable Influence of Elevated Salinity on the Fish Fauna of the Salton Sea



The Salton Sea: A Brief History and Biology

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Introduction

The Salton Sea is a shallow, hypersaline lake located below sea level in the Salton Basin (or Sink) of southern California (Figure 1). The Salton Sea is the largest body of water within the state of California. At a surface elevation of -227 feet, it covers approximately 381 square miles (243,718 acres). Despite its size, the Salton Sea is not well known nor is it well regarded by some who know of its existence. This low level of recognition for such a major body of water is due to: 1) the Sea's distance from large metropolitan areas, 2) its dependence upon agricultural drainage for continued existence, and 3) its water quality problems, both real and perceived.

Locale

The Salton Basin is a part of the San Andreas fault system, the main fault generally running along the eastern side of the basin. The Salton Sea divides the basin into the Coachella Valley to the north and the Imperial Valley to the south. The Mexicali Valley of Mexico is also part of the Salton Basin.

The Imperial Valley is a nationally important agricultural area, sometimes called the country's winter garden because of the wide variety of crops grown in the valley. Water for Imperial Valley is transported from the Colorado River via the All-American Canal which runs near the Mexico border. The major cities are El Centro, Brawley, and Calexico; the latter is contiguous with the Mexican city of Mexicali.

The Coachella Valley is also a major agricultural area, known for its dates and table grapes. Most Coachella Valley agriculture is irrigated with Colorado River water via the Coachella Canal, a branch of the All-American Canal which runs north along the eastern edge of the basin. There is also a substantial groundwater in the Coachella Valley. Besides agriculture, the Coachella Valley supports a significant resort/golfing industry historically centered around Palm Springs but now including such cities as Palm Desert, Rancho Mirage, Indian Wells, and La Quinta.

The Mexicali Valley of Mexico is

Formation

The Salton Basin is actually an extreme extension of the delta of the Colorado River (Figure 2). Periodically, as sediment deposition blocked the direct route to the Gulf of California, the Colorado River has changed course to flow west through the Salton Basin creating a a large lake called Lake Cahuilla. Over the past 1200 years Lake Cahuilla has been created four times, reaching a maximum elevation of 30 feet above sea level (Waters 1983). After a time, sediment deposition again forced the Colorado River back to its original route leaving the water in Lake Cahuilla to evaporate. After each filling Lake Cahuilla left its marks in the forms of ancient beach lines, particularly on the east side of the basin near the Coachella Canal, "bathtub rings" on the rock formations along the west side, and also in shallow shoreline fish traps constructed by Indians along rocky shores.

The sub-sea level was first realized by William Blake in 1853. Almost from its discovery then, have dreamed of importing Colorado River water.

The Salton Sea is a partial, modern incarnation of Lake Cahuilla formed when large flows from the Gila River of Arizona flooded the Colorado River and breached the headworks of an early Imperial Valley irrigation system (Figure 3). From _____ 1905 till _____ 1907, most of the Colorado River flowed into the Salton Basin. Not until the Southern Pacific Railroad constructed a trestle completely across the breach and poured tons of boulders into the break was the river redirected away from the Salton Basin (Kennan 1917).

Because, the flooding into the Salton Basin occurred at the turnout of an irrigation canal, the Salton Sea is almost always described as a man-made body of water. An argument can be made however, that in 1905 and 1906 the Colorado River would have flowed into the Salton Basin regardless of man's presence and rather than causing the creation of the Salton Sea, man may have halted another natural refilling of Lake Cahuilla. By examining tree ring data ______ () showed that the Gila River flows of 1906 were extraordinarily high: the highest in 150 years by a factor of 3 (Figure 4). In addition, it should be remembered that, for much of their lengths, the early irrigation canals utilized existing dry river beds, i.e. they followed. Also, the lower. These dikes may have prevented the river from breaching at other points, therefore creating the illusion that the canal turnout was

While filling, the Sea reached a maximum elevation of -196 feet and then began receding due to evaporation (Figure 2).

After its creation, the elevation of the Sea gradually fell, and its salinity rose, due to evaporation. The Sea's elevation began to rise again in the 1920s as agricultural development, and its associated drainage, continued to increase. Around 1950, salinity in the Sea reached oceanic levels and marine fish were successfully introduced creating a popular sportfishery. Together with stable elevation, the fishery made the Salton Sea a popular destination resort. More recently, the Sea's elevation has and the quality of the sportfishery has declined.

Water Sources and Balance

Table 1. (inputs)
rainfall & evaporation

Water Quality

bacti mostly cleaned up and can't survive in SS
occasional ag chemical discharge
residual DDE

Selenium

Colo R as source
low level in SS water (volatilization)
elevated in biota - eating warning

The Salton Sea Ecosystem

Productivity

The Salton Sea is a eutrophic (highly productive) ecosystem. Carpelan (1961a) estimated Salton Sea primary productivity (rate of photosynthesis) to be about four times that of coastal marine water (the most productive region of the oceans). The Salton Sea is also eutrophic by freshwater ecosystem standards (Table 1).

This high productivity is an important feature of the Salton Sea. It is ultimately responsible for the Sea's popularity with both waterfowl and anglers. Why is the Sea so productive?

The two nutrients which normally limit the productivity of aquatic systems are nitrogen and phosphorous. Because the inflow to the Sea consists largely of agricultural drainage means that the Sea receives large amounts of both of these nutrients (Table 2), quantities in fact which are normally considered acceptable only for much deeper lakes (Table 4). Nutrient levels within the Sea itself are characteristic of systems at the upper end of the productivity scale (Table 3).

The path of productivity within the Sea however, is not straightforward. The following is a brief review of the biology of the Salton Sea followed by a discussion of the Sea's trophic (feeding) interactions.

Phytoplankton

The immediate beneficiaries of the high nutrient input to the Salton Sea are planktonic algae, the phytoplankton. Over a dozen species of algae have been identified from the Sea (Carpelan 1958, 1961a; Arnal 1961).

Algae in the Sea include diatoms - algae which produce silicon cases (frustules) - and some green algae. The dominant group however, particularly in summer, is dinoflagellates, motile algae equipped with two flagella. Included in this group, and recorded from the Sea, are *Gymnodinium* and *Gonyaulax*, the two genera responsible for most "red tides" in coastal marine waters. Dinoflagellates utilize xanthophyll pigments, in addition to chlorophyll, for photosynthesis. Dinoflagellates range in color from colorless to brown or red and their occurrence partially explains the sometimes dark color of the Sea.

Zooplankton

Rotifers

Rotifers are small, relatively simple, invertebrates characteristic of freshwater environments. *Brachionus plicatilis*, the species in the Salton Sea, is a medium-sized (7 250 æm = .01 inch), completely planktonic rotifer. It is common in estuaries throughout the world. There is a large scientific literature on this species because of its value as food for fish larvae.

Several facets of the life history of *B. plicatilis* are optimal at high temperature (Rico-Martinez and Dodson 1992, Snell 1986). *B. plicatilis* feeds most effectively on particles over 2 æm, i.e. it has only a mediocre ability to feed on bacteria so algae and protozoa are its dominant food (Vadstein et al. 1993).

Like most rotifers, *B. plicatilis* is generally parthenogenetic (females producing females) with the occasional appearance of males resulting in the sexual production of resting eggs. High salinity and temperature make production of males less likely and inhibit the hatching of resting eggs (Hino and Hirano 1984; Lubzens et al. 1980, 1985, 1993; Minkoff et al. 1983).

Epp and Winston (1977) reported that *B. plicatilis* is essentially an osmoconformer, although slightly hyperosmotic, and interpret this as an indication of marine ancestry for this species. A review of the literature led Miracle and Serra (1989) to suggest that tolerance to high salinity increases at higher temperature. Population growth apparently ceases at 50 ppt (Pozuelo and Lubian 1993).

In the Salton Sea, *B. plicatilis* is most abundant in summer and autumn (Carpelan 1961). It is undoubtedly an important food item for the early life stage of Salton Sea fish.

Copepod

Copepods are small planktonic crustaceans with planktonic larvae (nauplii). The copepod in the Salton Sea was originally described as *Cyclops dimorphus* (Kiefer 1931, Johnson 1953) but has now been synonymized with *Apocyclops dengizicus* (Lindberg 1940, Kiefer 1967). *A. dengizicus* occurs in saline lakes worldwide (Kiefer 1967, Bayly 1972).

A. dengizicus occurs year-round in the Salton Sea (Dexter 1993) but is most abundant from mid-summer through autumn (Carpelan 1961b). It apparently consumes both phytoplankton (Carpelan 1961b) and rotifers (Dexter 1993) in the Salton Sea..

Adult *A. dengizicus* can survive salinities up to 107 ppt for extended periods but population growth stops at salinities over 57 ppt (Dexter 1993).

Benthos

Foraminifera

Foraminifera are amoeba-like protozoa which secrete calcium carbonate cases (tests) with pores through which pseudopods for locomotion and feeding extend. They are characteristically marine organisms.

Foraminifera are abundant members of the benthos of the Salton Sea; over two dozen species have been recorded (Rogers 1949, Arnal 1961). They feed on bacteria and the rain of detritus (dead organic matter) from the productive plankton of the Sea.

Pileworm

The pileworm, *Neanthes succinea*, is a widely distributed north Atlantic species of polychaete annelid apparently introduced to the California coast when Virginia oysters were introduced into San Francisco Bay in 1869 (Carlton 1979). It tolerates salinities as low as 14 ppt (Fong 1991) and can reach 460 mm (18 inches) in length but is generally much smaller in the Salton Sea (Hartman 1936).

N. succinea usually constructs a U-shaped tube in the sediment. It is a deposit feeder, ingesting substrate and digesting the organic fraction; it is relatively unselective as to particle size (Fong 1987). *N. succinea* has a higher optimal temperature and tolerates lower oxygen levels better than other species of *Neanthes* (Kristensen 1983a, b).

In the Salton Sea, *N. succinea* occurs throughout the Sea in winter but is most abundant in mid-depth sediments where there is a confluence of high organic sediment content (which increases with depth) and sufficient oxygen (which decreases with depth). In summer, *N. succinea* disappears from the deeper areas, apparently due to low oxygen (Carpelan and Linsley 1961b). Worms are often missing their tail segments, presumably a result of feeding activity by fish when they protrude from the worm tubes.

Like many nereid worms, *N. succinea* reproduces by metamorphosing into sexually mature forms, epitokes, which then swarm at night, near the water's surface, fertilizing eggs which develop into planktonic larvae. In many species, and in other populations of *N. succinea*, swarming is a relatively infrequent, sometimes annual, event synchronized by photoperiod and phases of the moon (Hardege et al. 1990, Fong 1991). In the Salton Sea, although spawning is most frequent in spring and autumn, it occurs virtually throughout the year (Carpelan and Linsley 1961b) and does not appear strongly related to lunar cycle (Carpelan and Linsley 1961a). The larval stage lasts about two weeks; worms can mature within 90 days.

Atokous (fully grown but sexually immature) *N. succinea* can tolerate salinities up to 67.5 ppt (Hanson 1972). Production of epitokes however, is depressed at 55 ppt and fertilization of eggs at 45 ppt (Kuhl and Oglesby 1979).

Barnacle

Barnacles are highly modified crustaceans; the great 19th century geologist Louis Agassiz described them as "nothing more than a little shrimplike animal, standing on its head in a limestone house and kicking food into its mouth." Like most crustaceans they have a planktonic nauplius larvae but, in addition, there is a non-feeding cypris larva immediately prior to settling and metamorphosis.

Balanus amphitrite is a western Atlantic species of barnacle which has, within the past century, spread throughout the world, apparently by hitchhiking on ships. It appeared in Hawaii in 1915, San Diego in 1921, Suez in 1924, northern Europe in 1929, and San Francisco in 1939 (Morris et al. 1980). It is now considered cosmopolitan in warm seas, particularly bays, where summer temperatures exceed the 20°C required for reproduction.

The Salton Sea population, *B. amphitrite* saltonensis (Rogers 1949), originated around 1943 with barnacles transported via Navy buoys or flying boats from San Diego Bay (Hilton 1945). Flowerdew (1985) compared the genetic composition of six populations of *B. amphitrite* and recommended eliminating *B. a. saltonensis* as a subspecies, but Raimondi (1992) detected differences in larval morphology and development which remained consistent during culturing, and which therefore, are probably attributable to genetic differentiation.

In the Salton Sea, barnacle larvae can be found in the plankton through most of the year but predominantly in spring and early summer (Carpelan 1961).

Other Species

Hurlbert (personal communication) has suggested that some benthic species which are now only locally abundant might become more important if fish are eliminated. These species include the amphipod (crustacean) *Gammarus mucronatas* and the water boatmen (insect) *Trichocorixa* sp.

Fish

Desert Pupfish

The desert pupfish, *Cyprinodon macularius*, is the only fish species endemic (native) to the Salton basin. It is a small (2-3 inch) member of the killifish family (Cypridontidae). The range of the desert pupfish originally extended across northern Mexico and the Colorado River delta into southern Arizona (Miller 1943), and probably included backwaters along the lower Colorado River (Turner 1983).

Desert pupfish are extremely tolerant of a wide range of physical conditions. The adults can survive oxygen concentrations as low as 0.2 mg/liter (Lowe et al. 1967) and salinities from freshwater (Cowles 1934) to almost 90 ppt (Barlow 1958a). Estimates of adult upper temperature tolerance range from 44.6°C (112.3°F) (Lowe and Heath 1969) to 53.3°C (128°F) (Jordan and Richardson 1929). Their eggs can develop in temperatures up to 35.7°C (96.3°F) and salinities of 70 ppt (Kinne and Kinne 1962, Sweet and Kinne 1964). Growth is faster at 35 and 15 ppt than at 55 ppt (Kinne 1960).

Desert pupfish are shallow water fish. They can feed and spawn in water 3 cm (1.2 inches) deep (Schoenherr 1985). The males generally establish territories and spawn in water less than 15 cm (6 inches) deep (Kynard and Garrett 1979); non-territorial males are reported to sleep in "the shallowest possible water" (Barlow 1961). They are capable of burrowing into sediment to escape predators (Barlow 1961), excessively high or low temperatures (Schoenherr 1988), and possibly also to withstand temporary drying of their habitat. Pupfish move to deep waters only to escape high temperatures (Barlow 1958b).

Desert pupfish are omnivorous, consuming algae, detritus, insects, and small crustaceans (Cox 1972, Naiman 1979). They spawn whenever the temperature is greater than 20°C (68°F) (Kinne 1960, Moyle 1976); the adhesive eggs are laid on the bottom or, possibly, on vegetation (Schoenherr 1988).

Through the 1950s, desert pupfish were abundant in the Salton Sea; Barlow (1961) reported schools of over 10,000 juvenile pupfish along the shore of the Sea. During the 1960s however, the desert pupfish population declined markedly (Crear and Haydock 1971). By 1978, desert pupfish could be found only sporadically (Black 1980).

The decline of desert pupfish was probably due to the introduction of two fish species: tilapia and sailfin mollies. The mechanism of replacement is behavioral interference with pupfish reproduction: Matsui (1981) demonstrated that tilapia and sailfin mollies reduce pupfish reproductive success by interfering with the territorial and courting behavior of desert pupfish. Schoenherr (1985) suggested that mollies excluded desert pupfish from Salton Sea shoreline pools while juvenile tilapia did the same in irrigation drains.

Regardless of the cause, the decline of the Salton Sea and other desert pupfish populations caused the species to be listed as endangered by the California Fish and Game Commission in 1980 and by the U.S. Fish and Wildlife Service in 1986 (USFWS 1986). More recently, CDFG surveys found desert pupfish in a majority of the irrigation drains entering the Sea, particularly at the north end of the Sea, and from a majority of shoreline pools along the southern and eastern shore of the Sea (Lau and Boehm 1991). This apparent partial recovery may be related to unusually high overwinter tilapia mortality _____.

Even when they were abundant, desert pupfish were not considered important in the Salton Sea ecosystem. They were not numerous enough to present serious food competition to other species and, although preyed upon by bairdiella, longjaw mudsuckers and wading birds, were "not important in the diets of any of these" (Walker, Whitney and Barlow 1961).

Sargo

The sargo (*Anisotremus davidsonii*) is a large (up to 17 inches) member of the grunt family (Haemulidae). They are commonly found near shallow structures such as rocks, kelp beds, and pilings from Santa Cruz to Baja California (Goodson 1988). Sargo eggs and larvae are planktonic.

The sargo population in the Salton Sea is derived from 65 fish transported from the Gulf of California in 1951; they became abundant by 1960 (Walker et al. 1961). During 1982-83, sargo constituted 28.3% of the sportfish catch, just edging out bairdiella as the second most commonly caught species (Black 1985). An average of 0.413 sargo were caught per hour of angling; they were the fish most commonly caught by jetty anglers. Sargo caught by anglers averaged 23 cm (9.1 inches) in length and 280 g (0.62 lb) in weight, with maxima of 35 cm (13.8 inches) and 1010 g (2.23 lbs).

Hanson (1970) reported that 96-hour mortality (without acclimation) of juvenile sargo increased at salinities over 50 ppt and that none survived at 62.5 ppt. Brocksen and Cole (1972) found sargo food utilization to be more efficient at 33 ppt than at 37-45 ppt.

Lasker et al. (1972) detected increased larval mortality at salinities of 40 ppt and higher; they also reported a high incidence of larval abnormalities, particularly bent tails. Matsui, Lattin et al. (1991a) reported that larval sargo mortality was markedly higher at 45 ppt and above than at 40 ppt. Matsui, Bond et al. (1991) reported a decline in the abundance of late larvae over the period 1987-89 which they related to increasing salinity during that period. Matsui et al. (1992) reported that about 8.2% of all sargo larvae collected during 1987-89 were deformed, most with retarded nervous system development.

Bairdiella

The bairdiella, *Bairdiella icistia*, known in the Salton Sea area as gulf croaker, is a small member of the croaker family (Sciaenidae), native to the Pacific coast of Mexico. A related species, *Bairdiella chrysura*, the silver perch is common in Atlantic and Gulf of Mexico estuaries. Bairdiella can be distinguished from young orangemouth corvina (below) by an anal spine longer than the anal fin rays.

The Salton Sea bairdiella population originated with 67 fish introduced from the Gulf of California in 1950-51 (Walker et al. 1961); they had become abundant by 1953 (Walker et al. 1961). An apparent genetic founder effect in the Sea's bairdiella population is detectable in the form of a low occurrence of rare alleles, although the overall rate of genetic heterozygosity is comparable to other fish populations (Beckwitt 1987).

The bairdiella diet is dominated by pileworms, particularly swimming pileworms, i.e. the spawning epitokes (Quast 1961). Bairdiella's dependence on pileworms is apparently reflected in both their daily and seasonal movement patterns. Bairdiella are more active and do most of their feeding after sunset when pileworms spawn. They are more abundant near shore beginning in spring, peaking in late summer, and then apparently spend the winter in deeper parts of the Sea (Whitney 1961a). This correlates with the distribution of pileworms, which are eliminated from the deeper parts of the Sea by low oxygen levels during summer. Bairdiella's condition factor (a measure of plumpness) appears to fluctuates in relation to pileworm spawning (Whitney 1961a); mass bairdiella mortality episodes have been related to poor condition (Quast 1961).

May is the peak spawning month for bairdiella (Whitney 1961a). Spawning takes place in early evening; the eggs are planktonic.

During 1982-83, bairdiella ranked third (just behind sargo) as the species most frequently caught by Salton Sea fishermen, making up 28.1% of the total catch. An average of 0.410 bairdiella were caught per hour of angling (Black 1985). Bairdiella caught by anglers averaged 24 cm (9.5 inches) in length and 160 g (0.35 lb) in weight, with maxima of 41 cm (16.1 inches) and 760 g (1.68 lbs).

Hanson (1970) reported that juvenile bairdiella transferred directly to higher salinities tolerated 52.5 ppt for 96 hours, although there was 60% mortality at 55 ppt. Mortality of yearling bairdiella started at 52.5 ppt (40%) and increased until no fish survived at 75 ppt. Brocksen and Cole (1972) found that, over a salinity range of 29 to 45 ppt, bairdiella food utilization was most efficient at 37 ppt. Lasker et al. (1972) detected increased larval mortality at salinities of 40 ppt and higher; they also reported a high incidence of larval abnormalities, particularly bent tails. Matsui et al. (1992) reported that about 2.2% of all bairdiella larvae collected during 1987-89 were deformed, most with retarded nervous system development. Matsui, Bond et al. (1991) found a decline in the abundance of bairdiella eggs and early larvae over the period 1987-89 during which salinity rose from 38 to 44 ppt, although the abundance of late larvae increased.

May (1975a, 1975b) has done detailed work on the effect of salinity and temperature on various aspects of bairdiella reproduction. The activity time of bairdiella spermatozoa falls from 3 minutes at 35 ppt salinity to 1.5 minutes at 55 ppt (May 1975a), although it's considerably longer at lower salinities. Fertilization success and hatching rate decline at salinities over 45 ppt and 40 ppt, respectively. Incubation at 30°C reduces the hatching rate compared to 27°C. Larvae reared at 30øC and salinities over 40 ppt had a notable frequency of spinal deformities. Hatched larvae can tolerate temperatures up to 31°C and salinity up to 45 ppt for 72 hours (May 1975b). May (1976) found that fertilization success was higher in Salton Sea water than in ocean water but larval survivorship much lower. By using charcoal filtration to remove organic contaminants and membrane filtration to elimination protozoan infestations, May related these results to the ionic composition of Salton Sea water.

Tilapia

Tilapia are members of the family Cichlidae, native to Africa but now distributed worldwide because of their popularity in aquaculture. Because of their importance in aquaculture, there is a large scientific literature on several tilapia species, including *Tilapia mossambica*.

The tilapia in the Salton Sea is a mouthbrooding species most similar to *Tilapia mossambica* and may be derived from several sources. Prior to 1963 the Arizona Game and Fish Department introduced *T. mossambica* into canals and drainage ditches leading to the Colorado River; from there they could have spread to the Imperial Irrigation District (IID) and Coachella Valley Water District (CVWD) irrigation systems (St. Amant 1966b). In 1964, *T. mossambica* were found to have escaped from an aquaculture pond into a small creek and drainage sump in the Mineral Spas area east of the Sea (St. Amant 1966a). In 1966 and 1967 the California Department of Fish and Game stocked *T. mossambica* into Wiest Lake on the Central Main Canal portion of the IID canal system (Hoover 1971). And from 1971 through 1982 *Tilapia zilli* (redbelly tilapia) were imported, under CDFG permit, by IID and CVWD for experiments in aquatic weed control in irrigation canals (Pelzman 1973). Since the Salton Sea tilapia are mouthbrooders, while *T. zilli* keeps its eggs in the nest, importation by the irrigation districts appears to be least likely source of the Salton Sea's tilapia, although *T. zilli* has been found in irrigation drains around the Sea (Schoenherr 1979).

T. mossambica feeds on a variety of foods - zooplankton, phytoplankton, and benthic detritus - and may switch among foods on a seasonal basis (Maitipe and De Silva 1985). *T. mossambica* does not filter planktonic algae as efficiently as other tilapia species (Robinson et al. 1990) but can grow on a pure phytoplankton diet (Gaigher 1982). The dominant food items however, are usually detritus and benthic algae (Man and Hodgkiss 1977, de Moor et al. 1986). Benthic feeding is accomplished by repeatedly biting into the substrate at a 45ø angle, leaving the bottom pockmarked with small depressions (Bowen 1979).

Male *T. mossambica* build nests about 50 cm (20 inches) in diameter in shallow water. The nests are usually constructed in clusters near sheltered areas (De Silva and Sirisena 1988). The female lays her eggs, the male swims over them releasing sperm, and the female immediately turns and picks the fertilized eggs up into her mouth. The larvae may receive some nutrient support from the mother during mouthbrooding (Kishida and Specker 1994).

During 1982-82, *T. mossambica* was the species most frequently caught by Salton Sea fishermen in general, and boat and shore anglers in particular, making up almost 41% of the total catch. An average of 0.595 tilapia were caught per hour of angling (Black 1985). Tilapia caught by anglers averaged 27 cm (10.6 inches) in length and 375 g (0.83 lb) in weight, with maxima of 45 cm (17.7 inches) and 1,580 g (3.48 lbs). No redbelly tilapia were found during this creel survey.

T. mossambica shows physiological signs of osmoregulatory collapse at 15°C (Smit et al. 1981); mortality occurs from 9.5°C (Behrends et al. 1990) to 15°C (Stauffer 1986). At low temperatures, stress impairs the immune system and the proximate cause of mortality is often fungal infection (Oldewage and As 1987, Behrends et al. 1990). *T. mossambica* can tolerate temperatures as high as 37°C and their preferred temperature is about 34-35°C (Stauffer 1986), although growth is slower at 35°C than at 30°C (Price et al. 1985).

The salinity tolerance of tilapia has been most recently reviewed by Stickney (1986). Five to 10 week old *T. mossambica* can tolerate 70 ppt for indefinite periods (Potts et al. 1967). Juvenile and adult T. mossambica can be acclimated to 60 ppt (Assem and Hanke 1979, Kültz and Onken 1993, Kültz and Jürss 1993). Popper and Lichatowich (1975) reported that *T. mossambica* reproduction was so prolific at salinities up to 49 ppt that it was necessary to introduce predators for population control.

There is conflicting evidence on the optimal salinity for *T. mossambica*. It is more susceptible to starvation (Jürss et al. 1984) and organic pollutants (Dang, 1986) at high salinity (i.e. seawater) and respiration is generally lower in fresh water (Job 1969). On the other hand, growth is generally faster at higher salinities (Canagaratnam 1966, Uchida and King 1962).

Orangemouth Corvina

The orangemouth corvina, *Cynoscion xanthulus*, is a large member of the croaker family (Sciaenidae), native to the Pacific coast of Mexico. Several related species, including spotted seatrout, *Cynoscion nebulosus*, and weakfish, *Cynoscion regalis*, are commercially fished along the Atlantic coast.

The Salton Sea corvina population originated with approximately 250 fish imported from the Gulf of California from 1950 to 1956. By 1957, the Sea's population was estimated at 800,000 fish (Whitney 1961b).

Young of the year corvina over two inches length feed largely on pileworms, competing for food with bairdiella. By their second year corvina have reached 159 mm length (6.26 inches) (Anderson 1971) and are largely feeding on bairdiella (Whitney 1961b) and, since their introduction, presumably tilapia. Other species such as sargo and mudsuckers are also readily consumed.

Whitney (1961b) reported anecdotal accounts suggesting that corvina may congregate near freshwater inflows to spawn. There are also some indications that Salton Sea corvina spawn in autumn as well as spring. Over 1.5 million planktonic eggs can be produced by a single female (Prentice et al. 1989).

During 1982-83, corvina made up 2.9% of the sportfish catch; an average of 0.042 corvina were caught per hour of angling (Black 1985). Corvina caught by anglers averaged 59 cm (23.2 inches) in length and 2000 g (4.41 lbs) in weight, with maxima of 108 cm (42.5 inches) and 12,000 g (26.46 lbs). Walker et al. (1961) recorded a 32 lb corvina.

Hanson (1970) reported that 100% of juvenile corvina survived 96 hours without acclimation at 52.5 ppt and had survivorship over 90% at 55 and 57.5 ppt, but that mortality was complete at 62.5 ppt. Brocksen and Cole (1972) found that corvina food assimilation was more efficient at a salinity of 37 ppt than at 29 or 45 ppt and that oxygen consumption was lowest at 33 ppt.

Matsui, Lattin et al. (1991b) found that adult corvina continued to grow at salinities up to 55 ppt. Oocytes matured at salinities up to 50 ppt although spawning did not occur at 45 or 50 ppt, and egg mortality remained below 10% at salinities up to 55 ppt. Prorated data from Matsui et al. (1992) indicates that about 1.1% of all corvina larvae collected from the Sea during 1987-89 were deformed, most with retarded nervous system development. Matsui, Bond et al. (1991) found a decline in the abundance of corvina eggs and late larvae in the Sea over the period 1987-89 which they related to rising salinity.

Other Species

There are three other fish species common along the edge of the Sea and in the irrigation drains leading to it.

The longjaw mudsucker (*Gillichthys mirabilis*) is a large (5-8 inches) member of the goby family common on mudflats in California estuaries from San Francisco south and in the Gulf of California. The Salton Sea population is derived from 500 fish transported from San Diego Bay in 1930 (Walker et al. 1961). Mudsuckers survive low tides by burrowing into the substrate. They can tolerate low oxygen levels by breathing air through their highly vascularized mouth (Todd and Ebeling 1966) and are capable of some terrestrial movement (Todd 1968). They can survive for several days in freshwater and have been collected from water of 82.5 ppt salinity (Barlow 1963). Mudsuckers are also tolerant of high sulfide levels (Bagarinao and Vetter 1989). Their hardiness has made mudsuckers a popular baitfish. In the Salton Sea, mudsuckers consume pileworms, insects, smaller fish, and barnacles (Walker et al. 1961). Mudsucker males defend breeding territories around their burrows (Weisel 1947); the slightly adhesive eggs are laid on the sides of the burrows (Moyle 1976); the larvae are planktonic.

The sailfin molly (*Poecilia latipinna*) is a livebearer (family Poeciliidae) native to the Atlantic coast of North America from South Carolina to the Yucatan peninsula (Lee et al. 1980) where it is found in both fresh and brackish water. The sailfin molly is a popular species for scientific studies; its social behavior in particular (e.g. Sumner et al. 1994, Schlupp et al. 1994), has been extensively studied.

The Salton Sea population may have been established by escapees from a tropical fish farm in the 1960s (St. Amant 1966a). A second species of molly, the shortfin molly (*Poecilia mexicana = Poecilia sphenops*) is also occasionally collected from irrigation drains around the Sea (Schoenherr 1979).

Sailfin mollies generally feed on detritus and plant material and, opportunistically, on insect larvae (Harrington and Harrington 1961). They die if the water temperatures reaches 15°C (59°F); the juveniles generally prefer temperatures over 30°C (86°F) (Stauffer et al. 1985). Adults can tolerate salinities of 80 (Nordlie et al. 1992) to 87 ppt (Herre 1929).

The porthole livebearer (*Poeciliopsis gracilis*) is another livebearing species (family Poeciliidae). Its native distribution is Central America and southern Mexico (Lee et al. 1980). This species appeared in the Salton Sea in the early 1970s, possibly an escapee from a tropical fish farm (Mearns 1975).

Discussion

Lasker et al. 1972 noted that sargo and bairdiella eggs floated in Salton Sea water but not Pacific Ocean water from La Jolla and suggested that this was an indication of adaptation to Salton Sea salinity.

May 1976: [lack of planktonic fish +] high food availability (zoop) = high larval survivorship; makes up for poor larval survivorship due to odd ion makeup

Bairdiella and *Cynoscion* occur together in estuaries

Bairdiella mortality 1953-56 (Whitney 1961)

most salinity work based on seawater ionic composition - may not completely apply to Salton Sea

Walker, Whitney and Carpelan (1961) recommend addition of mysid/amphipod non carnivorous invertebrate to parallel pileworm in food chain; maybe other worms (*Capitella*)

Conclusions

Two traits stand out in this review of Salton Sea biota. First, the invertebrate fauna of the Salton Sea is, for the most part, a collection of highly successful, widely distributed, predominantly estuarine, species. It is not a simple transplant from the Gulf of California nor a highly specialized hypersaline fauna. Second, much of the seasonality common in the reproduction of marine species has been lost. This is undoubtedly an artifact of the southern California desert climate and has been a factor in the productivity of the Sea's fishery.

The path of productivity from the phytoplankton to the Sea's fishery is convoluted because of the lack of an adult planktivorous fish. The populations of the invertebrate herbivores (rotifers and copepods) can respond quickly to changes in algal abundance. This means there is almost always abundant food for larval fish. But the transfer of productivity via live organisms stops at this point. Without a predator to feed on them, the zooplankton die naturally and sink to the bottom of the Sea as detritus to be consumed by bacteria, foraminifera, and pileworms (Arnal 1961, Carpelan 1961).

The lack of an effective planktivorous fish means that the productivity of the Sea has to travel through the benthos before reaching the fishery. There is however, a question about the effectiveness of bairdiella, historically the most important forage fish, in benthic feeding. Whitney (1961) reported that the condition (plumpness) of bairdiella correlated closely with the occurrence of pileworm swarming. This implies that bairdiella could not reliably feed on pileworms directly from the bottom of the Sea. If pileworm swarming were as highly seasonal in the Salton Sea as it is in other habitats, it is possible that bairdiella would not survive in the Sea. This apparent benthic feeding limitation of bairdiella may also explain their partial replacement by *Tilapia mossambica*. *T. mossambica* has a well-developed ability to forage food directly from benthic substrate (Bowen 1979).

Whether via bairdiella or tilapia, the Salton Sea food chain leading to corvina, the primary sport fish, is five or six steps:

1) phytoplankton
2) zooplankton
3) (bacteria/foraminifera)
4) pileworm
5) bairdiella/tilapia
6) corvina

In most lakes, the chain to reach a similar-sized sport fish would be only four steps:

1) phytoplankton
2) zooplankton
3) planktivorous fish
4) piscivorous fish (sport fish)

In conclusion, the successful, eurytopic nature of the Salton Sea's invertebrate fauna seems to indicate continued resilience for the Sea's community as a whole, but the pattern and length of the food chain apparently places the sportfishery at considerable risk.

Search: "fish" and "osmoregulation"

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Table 1. Surface flows into the Salton Sea, 1980-1990.

Table 2. Primary productivity (mg carbon/m2/day) of the Salton Sea and classification levels for fresh waters.

Category	Productivity	Salton Sea
Ultraoligotrophic	<50	
Oligotrophic	50-300	
Mesotrophic	250-1000	
Eutrophic	>1000	1032

Salton Sea data modified from Carpelan (1961a)
Productivity categories from Wetzel (1983)

Table 3. Phosphate-phosphorous and total nitrogen inflows to the Salton Sea.

	Alamo R.	New R.	Other Imperial Valley Drains	Whitewater R.	Other Coachella Valley Drains	Total
PO4-P (mg/m3)	682	906	?	1031	?	
Total N (mg/m3)	9,745	6,794	?	13,693	?	
Water flow (AF/year)	600,000	450,000	100,000	100,000	50,000	1,300,000
Annual PO4-P load						
(kilograms)	504,741	502,890		127,172		1,134,893
(tons)	556	555		140		1,251
Annual total N load						
(kilograms)	7,012,344	3,771,720		1,689,007		12,473,071
(tons)	7,730	4,158		1,862		13,750

Nutrient data from RWQCB, 1980-1992

Table 4. Comparison of Salton Sea phosphate-phosphorous and total nitrogen concentrations (mg/m3) with those from lakes of recognized trophic status.

Classification	Phosphorous			Nitrogen		
	Mean	Range	Salton Sea	Mean	Range	Salton Sea
Oligotrophic	8.0	3-18		661	307-1630	
Mesotrophic	26.7	11-96		753	361-1387	
Eutrophic	84.4	16-386	345	1875	393-6100	
Hypereutrophic		750-2000				13,700

Salton Sea data from RWQCB, 1980-1992 Classification data from Wetzel (1983)

Table 5. Annual areal phosphorous and nitrogen loading (g/m2) of the Salton Sea and recommended loading levels.

Mean Lake Depth	**"Permissible"**		**"Dangerous"**		**Salton Sea**	
	P	N	P	N	P	N
5 meters	0.07	1.0	0.13	2.0		
10 meters	0.10	1.5	0.20	3.0		
50 meters	0.25	4.0	0.50	8.0		
100 meters	0.40	6.0	0.80	12.0		
150 meters	0.50	7.5	1.00	15.0		15.4
200 meters	0.60	9.0	1.20	18.0	1.19	

Nutrient data from RWQCB, 1980-1992 Recommended levels from Wetzel (1983)

Figure 1. Southern California, showing the location of the Salton Sea.
Figure 2. The Salton Basin, the Gulf of California, and the Colorado River delta.
Figure 3. Location of break in dikes allowing flow into Salton Basin (modified from Kennan 1917).
Figure 4. Historic flows of the Gila River based on tree ring data from ____ 19__).
Figure 5. Elevation and salinity of the Salton Sea, 1905-1994.
Figure 6. Examples of four dinoflagellate (left) and three other genera of algae recorded from the Salton Sea.
Figure 7. A live foraminiferan (left) showing the pseudopods extending through the calcium carbonate test, and the tests of three other genera recorded from the Salton Sea.
Figure 8. The rotifers *Brachionus plicatilis*, carrying a single egg, and *Synchaeta*.
Figure 9. An adult female cyclopoid copepod (carrying two egg sacs), a nauplius larva, and a harpacticoid copepod.
Figure 10. The three life stages of *Neanthes succinea*.
Figure 11. The three life stages of *Balanus amphitrite saltonensis*.
Figure 12. A male desert pupfish, *Cyprinodon macularius*.
Figure 13. A sargo, *Anisotremus davidsonii*.
Figure 14. A gulf croaker, *Bairdiella icistia*.
Figure 15. A mozambique mouthbrooder, *Tilapia mossambica*.
Figure 16. An orangemouth corvina, *Cynoscion xanthulus*.
Figure 17. A longjaw mudsucker, *Gillichthys mirabilis*.
Figure 18. Female (top) and male (bottom) sailfin mollies, *Poecilia latipinna*.
Figure 19. A porthole livebearer, *Poeciliopsis gracilis*.
Figure 20. A threadfin shad, *Dorosoma petenense*.
Figure 21. Trophic relationships among the biota of the Salton Sea.
Figure 22. Possible changes in fish fauna with rising Salton Sea salinity.